diameters. Although the total force on the impingement surface is the same for both nozzles, the SOJIN's higher mixing rate resulted in a lower peak pressure. Also, it was observed that the extended collar of the SOJIN performed like a subsonic diffuser. The pressure ahead of the nozzle dropped slightly when the mass flow was held constant and the operation was changed from standard in-line jet impingement to first-stage oscillation. The second-stage oscillation also decreased the pressure ahead of the nozzle for the same flow rate. Thus, the SOJIN decreases the flow pumping requirements.

Flow visualization studies in a separate experimental facility using a submerged water jet showed vortex shedding during oscillation that came in pulses somewhat similar to those observed by Yokobori et al.[9] and Crow and Champagne.[10] Acoustic measurements were taken with a decibel meter and a spectrum analyzer. It should be noted that the high-frequency oscillations are audible and advantageous for some situations, but may be objectionable for others. The nozzle used for the experimental results shown in Fig. 3 exhibited first-stage oscillations at 5000 Hz with strong harmonics existing into the ultrasonic range.

Conclusions

A SOJIN has demonstrated higher heat transfer than that of a standard jet nozzle close to a surface. No external power was required and the pumping requirements for the same nozzle mass flow as a standard jet nozzle were slightly reduced. In addition, the SOJIN distributed the pressure increase over the impingement surface area in a less concentrated manner than that of a standard jet impingement nozzle. Thus, inexpensive modifications of industrial systems are possible with the SOJIN, which has untapped application potential.

Acknowledgments

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Role of Mainstream Flow Velocity in Film Cooling in a Duct

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Introduction

MOST studies on film cooling available in the literature have been found to perform in the subsonic flow region, very few studies were done in the supersonic flow region. Goldstein et al.[1] experimentally studied the film cooling effects in a supersonic flow following a slot. In their work, they used a trip to trigger an oblique shock at a place upstream from the porous section where the mass injection occurred, and studied the film cooling effect from the trailing edge or the porous section to the impingement point of the reflected trip shock. They found that the Mach number was reduced from the boundary-layer trip over the usable portion of the tunnel floor. We believe that the portion of floor where the test data collected was still in the subsonic separated region because of the upstream boundary-layer trip. O'Connor and Haji-Sheikh[2] numerically studied film cooling by injecting a heated secondary airstream through a rearward-facing slot into a supersonic mainstream with a Mach number of 3.0. The secondary stream was injected with a blowing ratio (secondary-to-main), varying from 0 to 0.328 (Mach numbers of secondary stream were from 0 to 0.986). We noticed that the authors did not extend their studies to have the secondary flow injected across the sonic line (i.e., Mach number of 1). In their studies, the main flow separated because of the slot protruding into the flow region and the inviscid/viscous interaction of flows. A separated flow region was created from the downstream side of the slot to the place where the main flow (compressed shock) reattached. This separated flow was further extended downstream as the blowing rate increased. Notice that this region is essentially dominated by subsonic flow, regardless of its size. From the previous two film cooling studies, a question was raised as to whether the film cooling effect would exist if the secondary flow was injected supersonically into an already supersonic main flow. Since there are not many investigations in supersonic film cooling, the objective of the present work is to explore the causes and the fundamental physics involved in film cooling, especially in the supersonic flow region. The effects of both subsonic and supersonic inlet flows on film cooling is experimentally investigated. A simplified one-dimensional control volume model with mass addition is developed to determine the essential features involved in film cooling.

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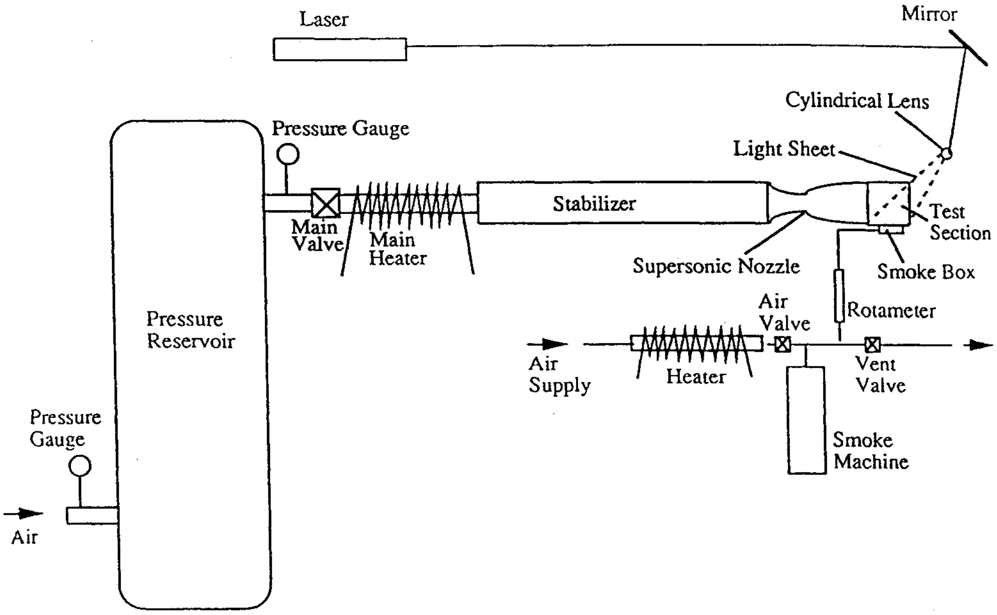

Fig. 1 Schematic of film cooling setup.

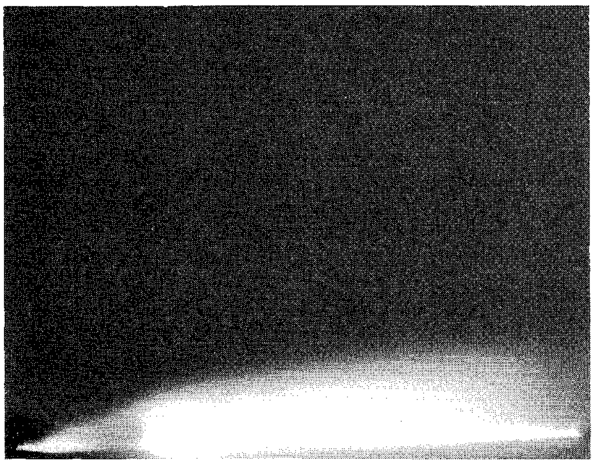

Fig. 2 Flow visualization in subsonic flow case.

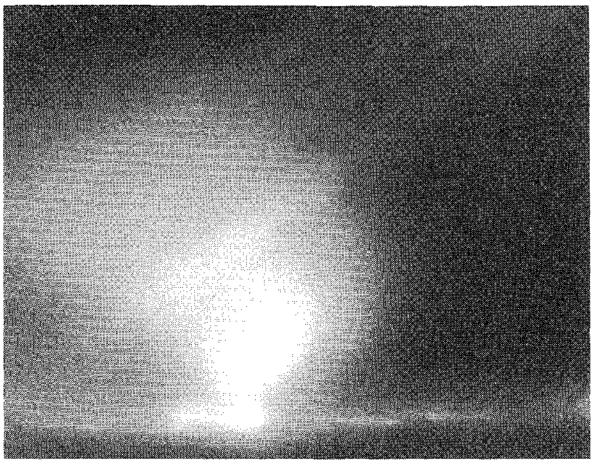

Fig. 3 Flow visualization in supersonic case.

Experimental Study of Film Cooling Effect

The experimental setup is shown in Fig. 1. The pressure reservoir was connected to an air supply. The stabilizer had a cross section of 25.4 × 50.8 mm and was 1.22 m in length. The nozzle had a throat of 15.5 × 25.4 mm and an exit cross section of 25.4 × 50.8 mm. The extended duct length of 41.4 mm served as the test section. A slanted hole with a 30-deg inclination angle was drilled on one side wall of the test section at a distance of 25.4 mm upstream from the exit. Smoke entered the test section via the smoke box with the aid of an airstream whose flow rate was regulated by an air valve. The air was preheated prior to its mixing with the smoke to prevent the occurrence of condensation inside the flow passage and the test section. The vent valve adjusted the injection flow rate that was measured using the rotameter. A cylindrical lens spread the laser beam into a light sheet that illuminated the test section. The throat curvature of a converging–diverging nozzle has the relationship of $z = 0.0552x^2 + 1$, where x and z are the coordinates of the throat curvature along and normal to the flow direction, respectively. The throat area was selected to be 15.5 × 25.4 mm, with the exit-to-throat area ratio of 3.28 to achieve a Mach number of 2–3 within a couple seconds at the inlet of the test section. The test began with opening the air supply valve, followed by turning on the air heater, main heater, and smoke generator. The smoke flow rate was set from 0.014 to 0.028 m^3/min, corresponding to Mach numbers of 0.25–0.5. The He–Ne laser illuminated the flowfield, and the video camera recorded the flow image changes in the vicinity of the opening of the smoke ejector in the test section. The main valve was quickly opened to start the supersonic wind tunnel. Within 2–3 s after the opening of the main valve, the reservoir pressure would fall from the maximum air pressure of 393–276 kPa, whereas the back pressure remained at ambient pressure. Before the main valve was opened, smoke came straight out from the ejecting hole. Upon the opening of the main valve, air flew through the test section with a continuously increasing subsonic flow speed, and smoke bent continuously towards the downstream wall, as shown in Fig. 2. As the airflow rate increased further, smoke became thinner. Once the choke condition was reached, a normal shock wave appeared at the throat migrating toward the exit of the test section. As soon as the shock wave passed through the smoke ejecting hole, the smoke bent towards the upstream direction against the main flow, as shown in Fig. 3. The test results lead to two observations:

1) Within subsonic flow regions the injected smoke covers the downstream walls, fulfilling the function of film cooling over the downstream heated chamber walls.

2) With supersonic flow passed through the secondary mass injection location, the injected flow stream bent towards the

upstream direction against the incoming main flow and created a stagnant flow region near the injection of secondary mass stream; it, therefore, provides no film cooling effect on downstream wall regions where the supersonic flow dominated.

Steady One-Dimensional Analysis with Simple Mass Addition

An attempt was made to model the complex flow phenomenon revealed by experiments with one-dimensional analysis. The analysis started with a one-dimensional control volume with constant cross-sectional area. A secondary mass stream with identical molecular weight, specific heat, and stagnation enthalpy as those of the main stream is added to this control volume. Neglecting heat transfer, frictional force, and external force on the control surface, the mixed stream (assuming two ideal gas streams mixed completely) are analyzed through a total of eight governing equations: continuity, momentum, energy, equation of state, Mach number relation, total temperature and pressure, impulse function, and entropy function. These comprise a system of eight equations with nine properties ratios. With the specification of property ratio of secondary mass rate, the remaining eight property ratios can be obtained. Details of the model analysis are available.[3] The results reveal that the property ratios depend on the injection mass flow rate, the Mach number of main mass flow, and the velocity ratio of secondary mass flow-to-main mass flow. It is observed that for subsonic flow, mass addition causes the impulse function, entropy, velocity, and Mach number to increase, whereas it causes the pressure, total pressure, density, and temperature to decrease. In contrast, the addition of mass in supersonic flow will cause the impulse function, entropy, density, pressure, and temperature to increase, with a decrease in the flow total pressure, velocity, and Mach number.

Results and Discussion

The simplified analysis predicted the essential features of the flow observed in the experimental work: The predicted increase in velocity or Mach number in the subsonic flow is consistent with the experimental observation of smoke flow bending, and acceleration in the downstream direction. The predicted reduction in velocity or Mach number in supersonic flow is consistent with the observation of flow back-reflecting, and deceleration in the upstream flow direction. Besides the flow velocity and Mach number, the model predicted the field temperature to decrease in subsonic flow and to increase for supersonic flow. Therefore, the film cooling effect prevails in subsonic flow because of the temperature decrease, but will not be materialized in supersonic flow because of the temperature rise in the flowfield. These findings are useful for providing a guideline to perform film cooling inside a supersonic flow region. The trick is to create a subsonic flow region near the critical area, and this subsonic flow region may result either from flow separation caused by flow channel geometrical changes or inviscid/viscous flow interaction such as external mass injection through a slot. Therefore, for supersonic flow, we can still obtain a subsonic flow region near the wall by manipulating the mass injection apparatus (e.g., slot height, mass injection angle, and speed) such that film cooling effect is plausible.

Conclusions

The effects of mass addition in both subsonic and supersonic flow on film cooling have been both experimentally and analytically investigated. Experimental observations have revealed film cooling to be effective in subsonic flow, but not in supersonic flow. A one-dimensional steady-state analysis has predicted that mass addition would cause enhancement in velocity or Mach number of the subsonic flow, but a reduction in flow velocity or Mach number of the supersonic flow. A film cooling effect prevails in subsonic flow because of the temperature decrease in the main stream, but it is absent in supersonic flow because of a temperature increase, leading to a conclusion that the film cooling effect cannot penetrate into a supersonic flow region.

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